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DAM PERFORMANCE AND SAFETY IN TROPICAL CLIMATES – RECENT DEVELOPMENTS ON FIELD MONITORING AND COMPUTATIONAL ANALYSIS

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Abstract: Earth dams are massive water-retaining structures that are used widely in the world for irrigation, water supply and hydroelectric energy generation. Many such dams are built every year and the International Committee on Large Dams (ICOLD) has gathered together experts from the world to work on preparing guidelines for design, construction and monitoring of such massive infrastructure. A potential failure of a large dam may potentially have significant effects on a huge area downstream, as the sudden release of the large volume of retained water can travel for large distances and destroy entire cities and even result in unfortunate fatalities.

It is therefore important to recognise the potential causes of failure of such dams and provide timely and effective measures to prevent any degradation or loss of stability. The main threats for dams are seismic activity, internal erosion, faulting and seasonal climate variations. The latter factor, i.e. climate changes, has not been studied widely and therefore there is a need for further understanding of the problem. In arid and tropical climates, e.g. the Mediterranean, Middle East, south Asia, large changes in the temperature and rainfall cause significant variations in the upstream reservoir level. This results in the dam rockfill undergoing cycles of wetting and drying which further causes permanent displacements and potentially cracking. Such structural response needs to be closely monitored, so that any potential leakage (and therefore erosion) is prevented.

This keynote paper presents an experimental study to investigate the effects of seasonal climate variations on the deformations of earth dams. A well-instrumented dam in Cyprus, the Kouris earth dam, which is the largest dam in the country is used as a case study. Long-term monitoring data from three-independent and different instrumentation sets are collected, processed and analysed. A periodic variation in the crest settlements is identified and thus relevant statistical analysis is performed to identify the dominant frequencies of fluctuations and to examine any relation between the dam crest settlements and the reservoir level changes. Subsequently, a nonlinear coupled hydro-mechanical finite element analysis is performed which models the entire stress history of the dam, i.e. layered construction, reservoir impoundment, consolidation and reservoir level changes. The latter finite element analysis attempts to identify the relative effects of soil consolidation and reservoir level changes on the induced dam displacements.

Keywords: embankment dams; reservoir; finite-element analysis; seepage; consolidation

1. Introduction

Many earth dams are built around the world and serve as water supply, irrigation or hydroelectric power infrastructure. Their long-term maintenance is important as this is crucial for their resilience and safety. The International Committee on Large Dams – ICOLD has identified some major threats for dam safety which include seismic activity (Elgamal et al., 1990; Pelecanos et al., 2013; 2015; 2016), internal erosion (Bridle & Fell, 2013; Shire & O'Sullivan, 2013, 2016), faulting, climate variation and change (Pytharouli & Stiros, 2005; Gikas & Sakellariou, 2008), hydraulic fracture etc. Climate variations are an important factor for dam safety as large seasonal changes (e.g. hot summers and cold winters) result in significant reservoir level changes which further affect the water pressures within the dam and the entire stress regime. It is therefore important to understand the impact of climate changes on the behaviour of earth dams and be able to predict and quantify its effects, especially if they become a threat for the dam's safety.

A wealth of studies exist in the literature which cover field monitoring (Kyrou et al., 2005; Dounias et al., 2012), laboratory experiments and computational simulations (Tedd et al., 1997; Alonso, 2005; Charles et al., 2008) for understanding dam performance and safety under various climate conditions. Many of these studies have raised the issue of reservoir-induced dam deformations and attempted to quantify this interaction. However, this is not an easy task and therefore more studies are needed in order to fully understand the effects of reservoir level changes on dam deformations and safety.

This paper presents a combined field monitoring and computational modelling study to understand and quantify the effects of climate variation and thus reservoir level changes on the performance of earth dams. Kouris dam, the largest dam in Cyprus was instrumented and the displacement data from over 25 years are analysed and further processed to identify a relationship between reservoir level and dam crest displacements. Subsequently, a nonlinear finite element analysis is performed which analyses the entire stress history of the dam, including reservoir level changes and confirms that indeed reservoir level changes affect dam crest deformations. It is therefore suggested that continuous long-term monitoring is needed to keep a consistent observation of the safety of earth dams.

2. Kouris Dam

2.1 Background & Geometry

Kouris dam is the largest and tallest dam in Cyrpus. It is a zoned earth-rockfill operated by the Cyprus Water Development Department (WDD) and serves as the main water storage facility in the country. It was built during 1984-1988 and its embankment consists of a central clay core of low permeability, followed by thin layers of fine and coarse filters. The upstream shell consists of terrace gravels, which are adjacent to the upstream filters and then river gravels covered by rip rap on the upstream dam slope with a small cofferdam at the upstream dam toe. The downstream shell consists in its entirety by terrace gravels with talus deposits, which rest on a thin drainage gallery. Its crest is 570m long and the embankment is 112m high with the highest level of its reservoir at 102m, and its total reservoir capacity is 115 million m^3. Figure 1 shows a cross-sectional view with the various soil layers.

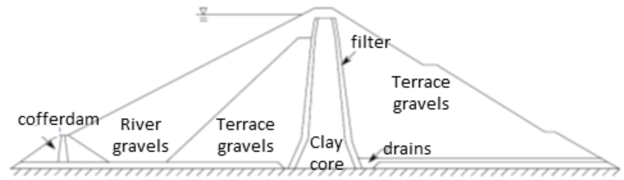


Figure 1: Geometry of the dam

2.1 Instrumentation

Three independent instrumentation sets are installed on the dam providing monitoring data about the deformations of the dam: (a) Embankment Crest Movement Indicators (ECMI), (b) a vertical geodetic network and (c) a three-dimensional (3D) geodetic network.

The first instrumentation network, installed in 1991, consists of an observation pillar, (fixed point) and six embankment crest movement indicators (ECMI) installed at the time of construction. The measurements of these points are being carried out (irregularly, monthly or bi-monthly) since 1990 by the Cyprus WDD. The horizontal distance and the height difference of each ECMI from the pillar was determined using a Leica TC1101 total station, which provides accuracy of ±2mm ±2ppm for the distance measurements and ±1" for the angle measurements.

Additionally, two modern geodetic networks were installed in 2006. A vertical (1D) and a three-dimensional (3D) control network. Generally, deformation monitoring is applied by the establishment, the measurement and the adjustment of such network. The vertical control network was established in 2006 (Constantinou, 2013). It consists of 7 control points. Six of them (R1-R6) are bronze benchmarks, located along both sides of the wall on the road at the crest of the dam and in a distance of about 100m between each other. The seventh point is the pillar T2 about 1 km far away, which serves as the fixed reference point of the network.

Three periods of measurements (July and December 2006 (Temenos, 2007) and June 2012 (Pantelidou, 2013)) were carried out for the determination of the height differences between the points by using either (a) the spirit leveling method, or (b) the accurate trigonometric heighting method (Lambrou, 2007; Lambrou & Pantazis, 2007, 2010). The latter two modern systems are extremely robust and much more accurate than the old initial system. Figure 2 shows the position of the instruments on the dam.

Figure 2: Instrumentation on the dam crest

3. Monitoring Data

3.1 Dam deformations

Figure 3 shows a comparison of dam deformations (both vertical and horizontal crest displacements) as those where obtained from the three different and independent instrumentation sets over the period 2006-2012. This is the period that was monitored from all three instrumentation sets. It is shown that a very good comparison is obtained between the three monitoring data sets which confirm their accuracy and reliability. Minor observed differences are well within what might be considered "noise" and therefore the monitoring system is proved to be working well.

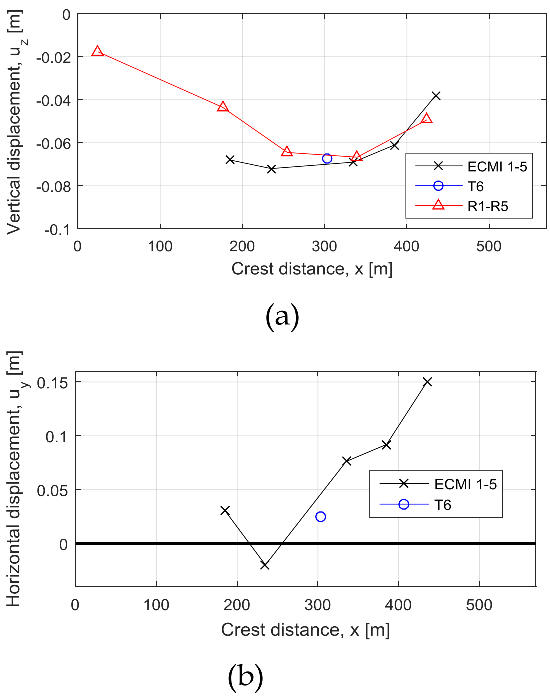
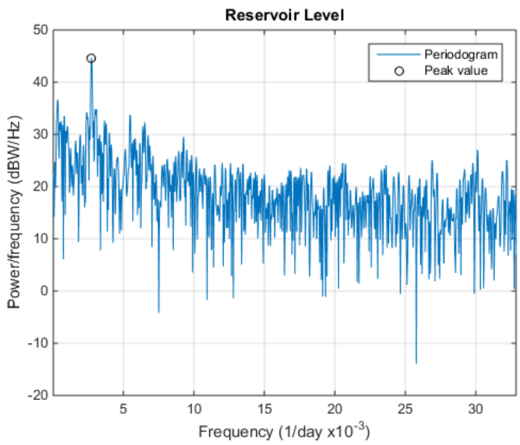


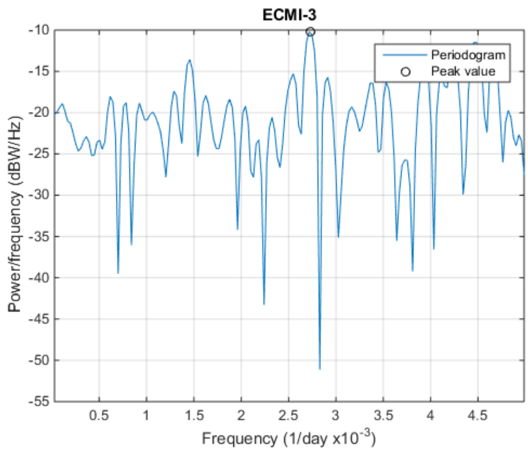
Figure 3: Dam deformations: profiles of (a) vertical and (b) horizontal dam crest displacements.

3.2 Statistical Analysis

Supplementary post-processing of the monitoring data was undertaken using statistical analysis. The aim of this exercise was to identify any relation between the reservoir level changes and the vertical displacement fluctuations and therefore recognise any causative relationship between the two. The time-histories of reservoir changes and crest settlements were analysed in the frequency domain and their dominant frequencies were determined. Because of the irregular time steps in the data, a Lomb-Scargle (Lomb, 1976; Scargle, 1982) periodogram was produced, which is similar to Fourier analysis but for non-equally spaced data. Figure 3 shows the periodograms for the reservoir level and the dam crest settlements. It is observed that both show clearly a single dominant frequency at 2.73 (1/day $\times 10^{-3}$), which means a period of 1000/2.73≈365 days, i.e. a full year. This supports the earlier observation that the reservoir level exhibits yearly peaks and this is agreement with earlier observations (Pytharouli & Stiros, 2005).



(a)



(b)

Figure 4: Statistical analysis of the monitoring data: Lomb periodogram of (a) reservoir level, (b) vertical displacements.

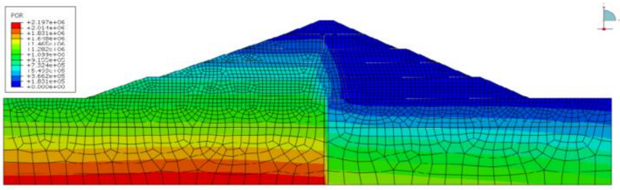
4. Finite element analysis

After a frequency relation between reservoir level changes and dam crest displacements was identified, an assessment of the relative effects of consolidation and reservoir level changes on the dam displacements was undertaken. For this, a relevant finite element analysis was conducted to investigate the long-term behaviour of the dam and understand the mechanisms of the observed long-term settlements of the dam crest. In particular, a comparison between the relative effects of soil consolidation and reservoir level fluctuations can be made.

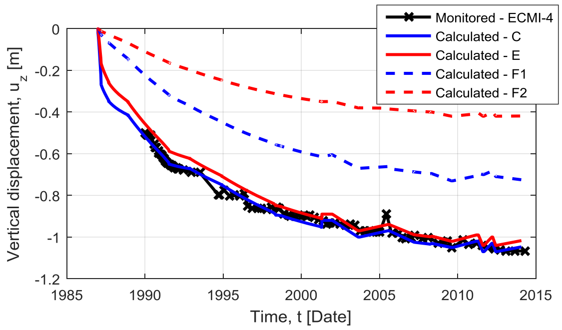
Two-dimensional (2D) plane-strain non-linear elasto-plastic transient coupled-consolidation finite element (FE) analyses were performed with the FE software ABAQUS/Standard. The analysis was performed in a number of stages to reproduce the exact stress history of the dam. Firstly, initial stresses were initiated with level ground and then the dam embankment was constructed in successive layers over a period of 12 months. Subsequently, the reservoir was impounded and its fluctuations followed the monitored time-history of the level of the reservoir.

Figure 5 (a) shows the pore water pressure distribution within the dam at the time of full reservoir. This shows the saturation of the upstream rockfill and the drop of hydraulic head within the dam due to the seepage through the low-permeability clay core and grout curtain. Figure 5 (b) shows the vertical displacements at various points within the dam (C: crest, E: mid-height of Embankment height, F1: shallow point in the foundation, F2: deep point in the foundation).

It is shown that there is generally a good match between the field-monitored (from ECMI-4) and numerically-predicted displacement values. It is also shown that there is a general trend of downward movements due to consolidation of the dam materials and that the reservoir fluctuations do not seem to have a severe impact on the dam settlements. On the same figure, the vertical displacements in the embankment and the two foundation layers (Points E, F1 and F2) are included too. It is shown that the consolidation settlement values of the foundation layers are considerably large and comparable to those of the dam crest, which would suggest that the consolidation settlements within both the dam embankment and the foundation contribute significantly to the overall crest settlements. This is due to the seepage of the excess pore water pressure generated in the embankment and the low-permeability foundation because of the construction of the large 110m embankment. This also suggests that the effects of the reservoir level fluctuations are not very significant and the dominant mechanism inducing long-term vertical crest displacements is indeed consolidation of the soil materials of both the dam foundation and the embankment. It is therefore concluded that there is no significant effect from the reservoir level fluctuations and that the majority of displacements is due to long-term consolidation.



(a)



(b)

Figure 5: Finite element analysis results: (a) pore water pressure distribution, (b) vertical displacements.

5. Conclusions

This investigation studies the long-term displacement behaviour of earth dams due to climate changes leading to variations of the reservoir level. The study considers the long-term monitoring data from a well-instrumented dam along with relevant nonlinear finite element analyses. The findings of this study may be summarised as follows:

(a) Consolidation of the dam embankment and foundation materials following the construction of the dam appears to be the main reason for the long-term dam settlements.

(b) There is an observed correlation between the dam displacements and reservoir level fluctuations, since their dominant frequencies are identical, which suggests seasonal variations of dam settlements.

(c) The contribution of reservoir level fluctuations on the displacements of the dam was found to be small compared to that of long-term consolidation.

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